Unified Breakdown Model of SOI RESURF Device with Uniform/ Step/ Linear Doping Profile *

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Abstract : A unified breakdown model of SOI RESURF device with uniform ,step ,or linear drift region doping profile is firstly proposed. By the model ,the electric field distribution and breakdown voltage are researched in detail for the step numbers from 0 to infinity. The critic electric field as the function of the geometry parameters and doping profile is derived. For the thick film device ,linear doping profile can be replaced by a single or two steps doping profile in the drift region due to a considerable uniformly lateral electric field ,almost ideal breakdown voltage ,and simplified design and fabrication. The availability of the proposed model is verified by the good accordance among the analytical results ,numerical simulations ,and reported experiments.

Key words : step doping profile ; linear doping profile ; SOI; RESURF; breakdown model

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1 Introduction

SOI technology has been paid great attention due to its high speed performance , latchup immunity , complete dielectric isolation , and low power dissipation[1]. Many simulations and experiments have shown that high breakdown voltage can be achieved in SOI RESURF devices with a linear doping profile in the drift region[2~6]. For example , Merchant *et al*.[4] and Zhang *et al*.[5] have fabricated the 600～700V SOI LDMOS with linear graded doping using the fine line lithography and high temperature anneals. For overcoming such difficulty in practice , Sunkavalli and Baliga[2] have suggested that the linear profile can be replaced by a single or two steps profile. Luo *et al*.[3] have also applied the step doping profile in RF device to bring about higher breakdown voltage ,lower on-resistance , reduced parasitic capacitance ,as well as improved drain current saturation behavior.

The breakdown model is one of the important research areas on SOI high voltage device. Li *et al*.[6] has proposed a complicated model to predict the breakdown voltage of double-drift region devices. Merchant *et al*.[4] and Zhang *et al*.[5] have developed two different models to describe the breakdown characteristics of linear doping profile. However ,only the corresponding special devices can be analyzed by those models because of the limitation of the theoretical hypothesis. In this work , we propose a unified breakdown model of SOI RESURF device with uniform ,step ,or linear doping profile in drift region by solving the 2D Poisson equation in different zones with coupling boundary conditions. Based on the model ,the impacts of geometric parameters on breakdown voltage and critical electric field are discussed for the varied step number from 0 to infinity. The first theoretical verification is developed that the single or two steps doping profile can substitute the linear graded drift region for the device with thick SOI layer because of good tradeoff between the perfor-

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mance and process. The model is evaluated using numerical simulations and reported experimental results.

2 Unified model

Figure 1 shows a schematic cross-section of the SOI RESURF device with step doping profile in drift region, and the sub-figure gives the distribution function of doping concentration. t_s and t_{ox} are the thick-

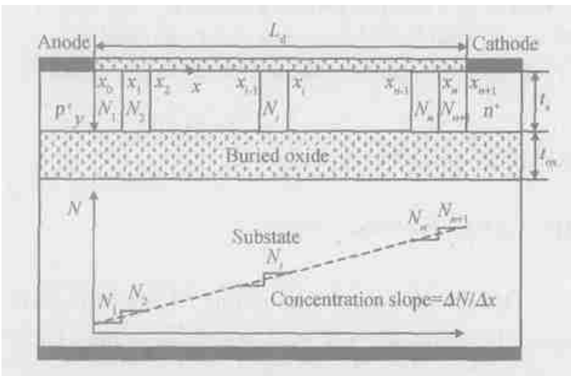

Fig. 1 Schematic cross-section of SOI RESURF device with step doping profile in the drift region

ness of SOI and buried oxide layers, respectively. ε_s and ε_{ox} are the permittivity of silicon and silicon oxide, respectively. L_d is the length of drift region. n is the step number. The drift region is equally divided into $n+1$ uniformly doped zones with the same length Δx. N_1 and ΔN are the doping concentration of the first zone and the concentration difference for the adjacent zones, respectively. Then the function of step doping profile can be given by

$$N_i = N_1 + \Delta N[x/\Delta x] = N_1 + (i-1)\Delta N,\quad i = 1, 2, \cdots, n+1 \tag{1}$$

where [ ] is a function to round the bracketed element toward zero. For $n = 0$ and $n = \infty$, equation (1) is simplified to $N(x) = N_1$ and $N(x) = N_1 + x\mathrm{d}N/\mathrm{d}x = N_1 + cx$, where c is the slope of concentration. Hereby, the uniform and linear doping profile can be treated as the specific cases of step doping profile at $n = 0$ and $n = \infty$, respectively.

When a high voltage V_d is biased on the cathode while the anode and the substrate are grounded, the drift region is completly depleted and the potential distribution of SOI layer $\phi(x, y)$ follows the 2D Poisson equation.

$$\partial^2\phi_i(x,y)/\partial x^2 + \partial^2\phi_i(x,y)/\partial y^2 = -qN_i/\varepsilon_s,\quad x \in [x_{i-1}, x_i],\ i = 1, 2, \cdots, n+1 \tag{2}$$

The boundary conditions can be obtained according to the minimization of vertical electric field at the surface[7] and the Gauss law at the interface between SOI and buried oxide layers.

$$\partial\phi_i(x,0)/\partial y = 0 \tag{3}$$

$$\varepsilon_s\partial\phi_i(x,t_s)/\partial y + \varepsilon_{ox}[\phi_i(x,t_s) - V_{SB}]/t_{ox} = 0 \tag{4}$$

where V_{SB}, the voltage applied on the substrate, is equal to zero for the grounded substrate. The two-order Taylor expansion is employed to approximate the vertical potential function[7], i.e.

$$\phi_i(x,y) = \phi_i(x,0) + y\partial\phi_i(x,0)/\partial x + 0.5y^2\partial^2\phi_i(x,0)/\partial x^2 \tag{5}$$

Substituting Eq. (5) into Eq. (2) and according to Eqs. (3) and (4), we can obtain the distribution of surface electric field as below:

$$E_i(x,0) = \left(V_i - \frac{qN_it^2}{\varepsilon_s}\right)\frac{\cosh[(x-x_{i-1})/t]}{t\sinh(\Delta x/t)} + \left(\frac{qN_it^2}{\varepsilon_s} - V_{i-1}\right)\frac{\cosh[(x_i-x)/t]}{t\sinh(\Delta x/t)},\quad i = 1, 2, \cdots, n+1 \tag{6}$$

where $t = (0.5 + C_s/C_{ox})^{1/2}t_s$, C_s and C_{ox} are the unit capacitances of the SOI and buried oxide layers, respectively, V_i and V_{i-1} are the surface potential applied at the boundaries of zone i, and can be solved based on the continuity of the surface electric field[11].

$$V_i = \begin{cases} V_{p^+n}, & i = 0 \\ \sum_{j=1}^{n} a_{ij}v_j, & i = 1, 2, \cdots, n \\ V_d - V_{n^+n}, & i = n+1 \end{cases}$$

$$a_{ij} = \begin{cases} \dfrac{\sinh(i\Delta x/t)\sinh[(n+1-j)\Delta x/t]}{\sinh(L_d/t)\sinh(\Delta x/t)}, & i \le j \\ \dfrac{\sinh[(n+1-i)\Delta x/t]\sinh(j\Delta x/t)}{\sinh(L_d/t)\sinh(\Delta x/t)}, & i > j \end{cases}$$

$$v_j = \begin{cases} \left[\cosh\dfrac{\Delta x}{t} - 1\right]\dfrac{q(2N_j + \Delta N)t^2}{\varepsilon_s} + V_0, & j = 1 \\ \left[\cosh\dfrac{\Delta x}{t} - 1\right]\dfrac{q(2N_j + \Delta N)t^2}{\varepsilon_s}, & j = 2, 3, \cdots, n-1 \\ \left[\cosh\dfrac{\Delta x}{t} - 1\right]\dfrac{q(2N_j + \Delta N)t^2}{\varepsilon_s} - V_{n+1}, & j = n \end{cases} \tag{7}$$

where V_{p^+n} and V_{n^+n} are the building-in potential of p^+n and n^+n junctions.

Equations (6) and (7) give the distributions of the surface electric field for the SOI device with n step doping profile. For uniform and linear profiles, they are simplified to

$$E(x,0) = \left(V_d - V_{n^+n} - \frac{qN_1 t^2}{\varepsilon_s}\right)\frac{\cosh(x/t)}{t\sinh(L_d/t)} + \left(\frac{qN_1 t^2}{\varepsilon_s} - V_{p^+n}\right)\frac{\cosh[(L_d - x)/t]}{t\sinh(L_d/t)}, \quad n = 0 \tag{8}$$

$$E(x,0) = \left(V_d - V_{n^+n} - \frac{q(N_1 + cL_d)t^2}{\varepsilon_s}\right)\frac{\cosh(x/t)}{t\sinh(L_d/t)} + \left(\frac{qN_1 t^2}{\varepsilon_s} - V_{p^+n}\right)\frac{\cosh[(L_d - x)/t]}{t\sinh(L_d/t)} + \frac{qct^2}{\varepsilon_s}, \quad n = \infty \tag{9}$$

Avalanche breakdown commences when the ionization integral along the drift region approaches one, i.e.

$$\int_0^{L_d} \alpha E^7(x,0)\,dx = \sum_{i=1}^{n+1}\int_{i-1}^{i} \alpha E_i^7(x,0)\,dx = 1 \tag{10}$$

where α is the ionization constant. Substituting Eq. (6) into (10), the breakdown voltage V_b can be solved.

Sunkavalli *et al*. and Luo *et al*. have presented that the electric field peaks appear at the boundaries of zones[2,3] and must be simultaneously equal to the critic electric field E_c at breakdown for an optimal structure[11], i.e.

$$E(x_i,0) = E_c, \quad i = 0,1,\cdots,n+1 \tag{11}$$

Substituting Eq. (6) into (11), the optimal doping distribution and the maximal breakdown voltage can be derived.

$$N_i = \frac{(2i-1)\tanh(0.5\Delta x/t)\,\varepsilon_s E_c}{qt}, \quad i = 1,\cdots,n+1 \tag{12}$$

$$V_b = 2(n+1)\tanh(0.5\Delta x/t)\,E_c t \tag{13}$$

where the building-in potentials of junctions, which is much lower than the voltage applied on the device, are ignored to illustrate a more clearly physical image. The critic electric field E_c is obtained by substituting Eqs. (6), (7), (12), and (13) into (10).

$$E_C = \cosh(0.5\Delta x/t)\left[\alpha(n+1)\int_0^{\Delta x}\cosh^7(0.5\Delta x/t)\,dx\right]^{-1/7}$$
$$= \frac{(n+1)^{-1/7}\cosh(0.5\Delta x/t)(2\alpha t)^{-1/7}}{[\sinh^7(0.5\Delta x/t)/7 + 3\sinh^5(0.5\Delta x/t)/5 + \sinh^3(0.5\Delta x/t) + \sinh(0.5\Delta x/t)]^{1/7}} \tag{14}$$

For linear doping profile, when $n \to \infty$, Eqs. (12), (13), and (14) are simplified to

$$N(x) = \frac{\varepsilon_s E_c}{qt^2}x$$
$$V_b = E_c L_d \tag{15}$$
$$E_c = (\alpha L_d)^{-1/7}$$

3 Results and discussion

Figure 2 shows the optimal profiles of lateral electric fields of the uniform, single step, two steps, and linear doping near breakdown. The surface analytical electric fields show fair agreements with the numerical simulations using the device simulator MEDICI. Two sharp peaks in electric field near the anode and cathode regions and a large dip in the middle of the drift region can be observed in SOI RESURF device with uniform doping profile. Hence the middle portion of the drift region supports only a small fraction of the voltage and a lower breakdown voltage is exhibited. For the step drift device, however, additional electric field peaks appear at the both ends of the divided zones. Consequently, the dips in the middle of the drift region become shallow with the increase of the steps and more voltage can be supported in the step drift region at breakdown. When the doping profile is linear, an ideal uniform lateral electric field independent of the SOI layer thickness is distributed on the surface of SOI layer according to the analytical and numerical results. The maximum breakdown voltage can be obtained for a given drift region length. By comparison between Figs. 2(a) and (b), a thin SOI layer leads to the increase of peaks and the decrease of dips of the electric field in the surface of drift region. Therefore, the improvement of electric field distribution is reduced for the thin film device using the step drift profile.

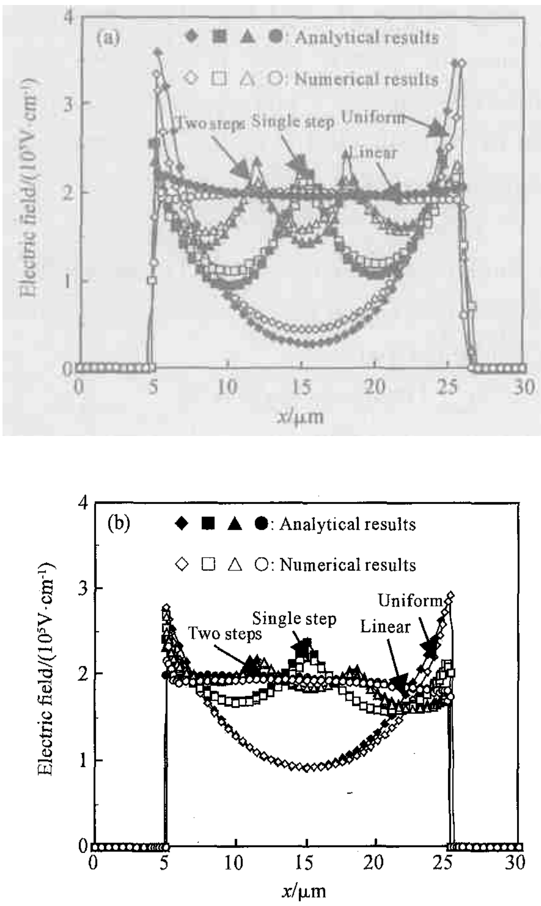

Fig. 2 Profiles of optimal surface electric field near breakdown for the different steps number (a) t_s = 1μm, t_{ox} = 3μm; (b) t_s = 3μm, t_{ox} = 3μm

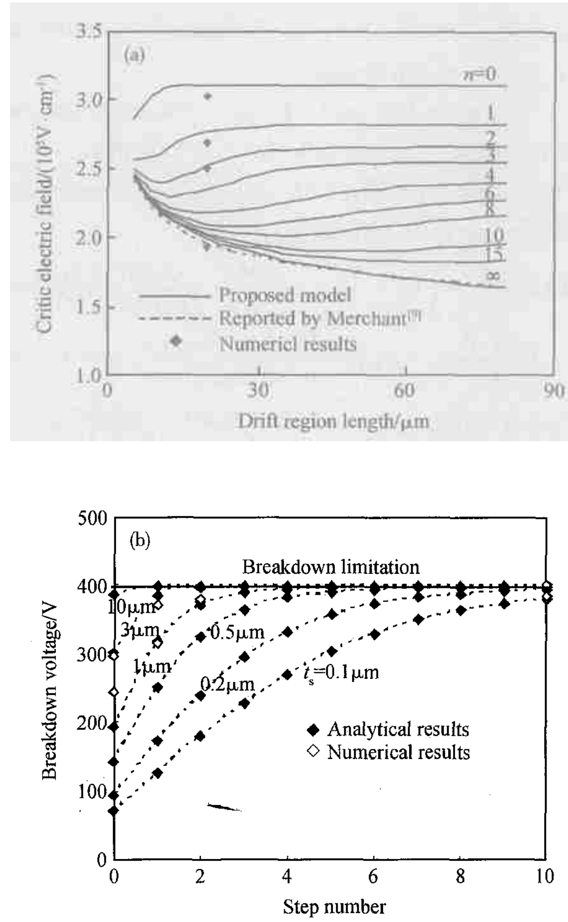

Fig. 3 Critic electric field and breakdown voltage for different steps numbers (a) Critic electric field as a function of drift region length; (b) Breakdown voltage as a function of steps number

Figure 2 also presents that the critic electric field, namely the electric field peaks at breakdown, varies with the step number and SOI layer thickness at the fixed drift region length and buried oxide thickness. Figure 3 shows more detailed analytical and numerical results. The relationship between the critic electric field and drift region length for the 3μm-thick SOI layer and 3μm-thick buried oxide layer is shown in Fig. 3(a). With the increase of drift region length, the critic electric field increases for few step numbers but decreases for many step numbers until a saturation value is reached. The critic electric field for a linear doping profile in drift region approaches the lowest limitation, which is exactly accordant with the results by Merchant *et al*.[9]. Figure 3(b) shows the dependence of breakdown voltage on step number for varied SOI layer thickness. When the doping profile is linear, i. e. $n = \infty$, the breakdown voltage is maximum and independent of the SOI layer thickness according to Eq. (15). For a few steps, however, dependence of the silicon film thickness on breakdown voltage is evident. From the figure, a high breakdown voltage needs 4～8 step numbers in drift region for the device with 0.1～1μm-thick SOI layer. This fact presents that the linear graded doping can not be substituted by the step doping in ultrathin and thin film devices due to the difficulties in practice. For a thick film device when t_s exceeds 3μm, a single or two steps can bring a drastically improvement of the breakdown voltage and hence the step doping can replace the linear profile due to easily fabrication[2]. Further increase in the number of steps in the drift region leads to only a relatively small increase in the breakdown voltage. The single step profile needs no additional masks compared to the linearly graded profile which requires a perforated mask utilizing fine line lithography and long-time high-temperature anneals[5].

Figure 4 illustrates that impact of the doping profile in drift region on breakdown voltage. Figure 4 (a) is the numerical and analytical results of the relationship between the concentration slop $\Delta N/\Delta x$ and breakdown voltage at a fixed concentration of the first region N_1.

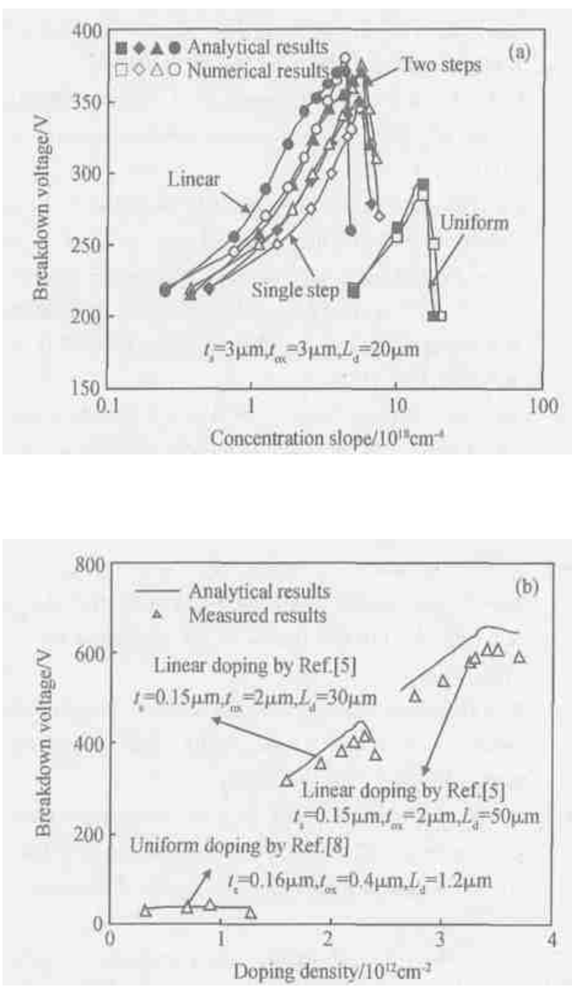

Fig. 4 Numerical, experimental, and analytical results of the breakdown as a function of the concentration slope (a) and the drift charge density (b)

The breakdown voltage increases with the increase of the step number. Figure 4(b) shows the dependence of the breakdown voltage on the charge density in the uniform and linear doping profiles with different drift region lengths. The charge density in the drift region was calculated by the integration of the doping concentration along the drift region. The proposed model is verified by a good agreement between the analytical model and measured data reported in earlier works[5,8]. It is shown in Fig. 4 that the breakdown voltage increases with the increase of the concentration slop and charge density in the drift region up to a maximum value, and then reduces with further increase of them, which is the typical RESURF phenomenon of SOI high voltage device[11].

Figure 5 shows the dependence of the breakdown voltage on the geometry parameters at the varied step number and fixed charge density in drift region. In order to achieve a better agreement between analytical and numerical results, the ionization constant α can be adjusted[10]. The new value using in the analytical model is 4.0×10^{-15}. Figure 5(a) shows the breakdown voltage of SOI RESURF devices scales up with increasing drift region length until a saturation value associated with the vertical breakdown is reached. A higher saturation breakdown voltage and a longer critic drift region length can be observed for the step and linear doping profiles in comparison with the uniform doping profile. Figures 5(b) and (c) demonstrate the influence of SOI layer thickness t_s and the buried oxide layer thickness t_{ox} on the breakdown voltage, respectively. The analytical and numerical results present that the optimum value of them should be adopted to maximize the breakdown voltage. The variety of these geometry parameters can lead to a movement of breakdown location from the cathode to the anode due to the RESURF effect[11,12]. As shown in these figures, the step and linear doping in drift region bring thinner optimal thicknesses of SOI and buried oxide layers and higher breakdown voltage.

4 Conclusion

A unified analytical model for analysis of the breakdown properties of RESURF SOI device with uniform, step, and linear doping profile in drift region is

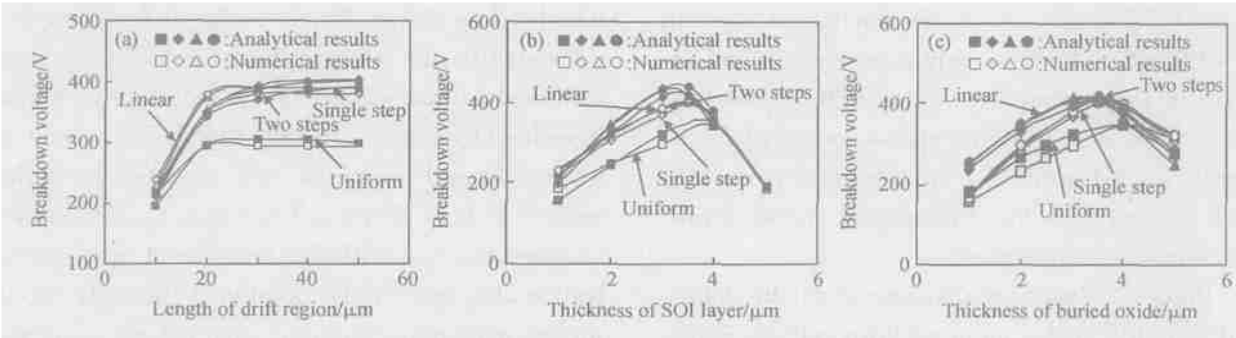

Fig. 5 Breakdown voltage as a function of drift region length (a) ,thickness of SOI layer (b) ,and thickness of buried oxide layer (c)

proposed in this paper. Based on the model and 2D semiconductor device simulator MEDICI, the critic electric field and breakdown voltage as the function of the device parameters is researched for the SOI device when the step number varies from 0 to infinite. It is proved theoretically for the first time that the single or two steps profile results in much higher breakdown voltage over the uniformly doped profile while providing simplification in design and processing when compared to the linearly graded profile in the device with a thick SOI layer.

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均匀、阶梯和线性掺杂漂移区 SOI RESURF 器件的统一击穿模型 *

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摘要: 提出了一个均匀、阶梯和线性掺杂漂移区 SOI 高压器件的统一击穿模型. 基于分区求解二维 Poisson 方程, 得到了不同漂移区杂质分布的横向电场和击穿电压的统一解析表达式. 借此模型并对阶梯数从 0 到无穷时器件结构参数对临界电场和击穿电压的影响进行了深入研究. 从理论上揭示了在厚膜 SOI 器件中用阶梯掺杂取代线性漂移区, 不但可以保持较高的耐压, 而且降低了设计和工艺难度. 解析结果、MEDICI 仿真结果和实验结果符合良好.

关键词: 阶梯掺杂; 线性掺杂; SOI; RESURF; 击穿模型

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